REFLECTOR ANTENNA SYSTEM INCLUDING A PHASED ARRAY ANTENNA OPERABLE IN MULTIPLE MODES AND RELATED METHODS

Field of the Invention

[0001] The present invention relates to the field of communications systems, and, more particularly, to antenna systems and related methods.

Background of the Invention

[0002] Steerable antennas are used in a variety of applications where transmissions are to be directed at different geographical locations or targets, or conversely where it is desirable to receive signals only from a particular direction. Perhaps the two most common types of steerable antennas are reflector antennas and phased array antennas. Reflector antennas include a reflector and a feed device, such as a horn, positioned at the focal length of the reflector. The reflector is mounted on a mechanical steering device, such as a gimbal, which directs the reflector at the intended target.

[0003] Reflector antenna systems have certain advantages. For example, they are relatively inexpensive, and they can achieve a fairly large scan angle. However, such antennas also have their drawbacks. More particularly, the mechanical steering components may be relatively heavy and/or bulky for a large reflector, they take a relatively long amount of time to change directions, and they may be prone to failure. Plus, to provide a large scan angle, the antenna system requires a large amount of clearance to move the reflector.

[0004] Phased array antennas include an array of antenna elements that can be electrically phased to steer and/or shape the antenna beam. Since phased array antennas do not require a reflector or mechanical steering equipment, they typically do not suffer from the weight or clearance constraints of reflector antennas. Moreover, they provide very rapid beam steering. Yet, phased array antennas are typically more costly to implement than reflector antennas, and they tend to suffer greater signal loss as the scan angle increases. While gain elements (i.e., amplifiers) and increased numbers of antenna elements can be used to offset such signal loss and achieve desired scan angles, this increases the footprint of the array, as well as its power consumption.

[0005] Some attempts have been made in the prior art to combine the benefits of both reflector antenna systems and phased array antenna systems. More particularly, antenna element arrays have been used as the feed device for a reflector. This allows beam steering to be

performed by electrically displacing the phase center of the feed array, rather than moving the reflector itself.

[0006] The basic principles involved in steering the beam of a reflector antenna are well known. However, these principles will be generally discussed herein with reference to a typical prime-focus reflector antenna system. A single feed structure is placed at the focus of the reflector and is designed such that the feed beamwidth fully illuminates the reflector. If the feed beamwidth is too wide, excess feed energy will spill over the edges of the reflector, reducing efficiency. If the feed beamwidth is too narrow, then the reflector is said to be under-illuminated and will have the gain and beamwidth commensurate with the area illuminated by the feed. In other words, under-illuminating a reflector antenna effectively creates a smaller reflector antenna which in turn has less gain and a larger beamwidth.

[0007] In actual practice, it can be desirable to slightly under-illuminate a reflector (e.g., designing the feed such that the edge of the reflector is illuminated 10 dB less than the center of the reflector) as a method to slightly reduce sidelobes and balance the efficiency of the resultant system. This is done because it is very difficult to design a reflector feed that only illuminates the reflector antenna. That is, there will almost always be some amount of spillover and amplitude taper across the reflector due to the antenna pattern of the feed. Regardless, the reflector feed is designed to produce a given beamwidth that illuminates the reflector surface in a desired manner.

[0008] If using a feed horn, for instance, this beamwidth control is achieved by proper choice of horn length and aperture. If an antenna array were used, however, the beamwidth is a function of the area of active portion of the array. Feeding more elements, or more precisely exciting a larger area of elements, will cause the beamwidth of the feed to narrow and become more directive. Either a single feed horn or a small array can be designed to properly illuminate a reflector antenna. To steer a beam in a reflector, one can displace the phase center of the feed antenna laterally, as opposed to axially, from the focus of the reflector nominally along what is referred to as the Petzval surface. The amount of beam steer is roughly equal to the angle formed by the displacement of the feed center to the center of the reflector.

[0009] To counter the disadvantages of mechanically moving a small feed antenna, attempts have been made to replace the mechanically-moved feed with a large array antenna. However, such implementations have been limited in their effectiveness. That is, if the element array is placed in the path of the antenna beam, the array has to be relatively small (typically less than 10%-15% the diameter of the reflector it is feeding as a rule-of-thumb) or severe signal blockage will occur causing undesirable degradation of the resultant antenna pattern and gain. That is, a large array will block transmitted signals coming off of the reflector, or block signals from reaching the reflector.

[0010] Yet, a small array may not be sufficient to provide desired scan angles. The array needs to be sized

such that a smaller subarray, sized to provide the required beamwidth to illuminate the reflector, can be electrically "moved" by turning array elements on and off, effectively providing the same function of mechanically moving the small array. In other words, in a large array a small portion of the array can be turned on (with all other elements off) to form the required feed array size. This small subarray can be moved, or migrated, among the larger array by turning off some antenna elements in the direction the subarray is to "move" away from, and turning on others in the direction the subarray is to "move".

[0011] This electrical movement of the feed subarray can take place much faster than in a mechanical system. Additionally, multiple clusters or subarrys of elements can be used to produce multiple beams off the reflector antenna. A disadvantage of such a system is that the required array size for large amounts of scan can be large and cause significant blockage. Since typically the active region is much smaller than the entire array, the amount of blockage and subsequent performance loss is not acceptable in many applications and may indeed be so bad as to cause the system to not function at all.

[0012] Another approach is to displace an array antenna so that it is not in front of the reflector, but is instead off to one side thereof. An example of such an antenna is disclosed in U.S. Patent No. 6,456,252. This patent discloses a multi-feed reflector antenna system in which feed elements of a feed array are located at the focal plane of the reflector, and to the side thereof. A repeater device located at a defocused plane between the

feed array and the reflector intercepts a cone angle between the feed array and the outside rim of the reflector. The repeater device includes a receiver array facing the feed array, and a transmit array facing the reflector. The repeater device receives an incoming wavefront from the feed array at the receiver array, and repeats the wavefront from the transmit array.

[0013] In the above-described system, the repeater device and feed array are both positioned to the side of the reflector. With such a side-feed arrangement, neither the repeater device nor the feed array are in the path of the antenna beam defined by the reflector. That is, they are not positioned between the reflector and the target, and thus will not block transmission signals coming off of the reflector, or signals directed at the reflector that are to be received. Yet, one drawback of using such an arrangement is that a significant amount of scan angle may be given up by offsetting the feed array from the path of the antenna beam.

Summary of the Invention

[0014] In view of the foregoing background, it is therefore an object of the present invention to provide an antenna system which incorporates advantages of both reflector antennas and phased array antennas and related methods.

[0015] This and other objects, features, and advantages in accordance with the present invention are provided by a reflector antenna system which may include at least one antenna reflector having an arcuate shape and defining a first antenna beam, and a phased array

antenna positioned in the first antenna beam. More particularly, the phased array antenna may include first and second arrays of antenna elements coupled together in back-to-back relation. The first array may face the at least one antenna reflector, and the second array may face away from the at least one antenna reflector. The phased array antenna may further include a controller connected to the first and second arrays of antenna elements which may be switchable between a reflecting mode and a direct mode.

[0016] More particularly, the controller when in the reflecting mode may cause a plurality of back-to-back pairs of first antenna elements from the first and second arrays to define at least one feed-through zone for the first antenna beam, and cause a plurality of second antenna elements in the first array to define at least one first active zone for the first antenna beam. Furthermore, when in the direct mode, the controller may cause a plurality of antenna elements in the second array to define at least one second active zone for a second antenna beam.

[0017] Accordingly, because the phased array antenna when in the reflecting mode has a feed-through zone, it advantageously allows the first antenna beam defined by the at least one antenna reflector to pass therethrough. As such, a relatively large phased array antenna may be placed in front of the at least one antenna reflector, yet without the large amount of blockage that would otherwise occur by similarly using a comparably sized prior art array antenna.

[0018] Moreover, the phased array antenna may be used to electrically steer the antenna beam, and thus a mechanical steering assembly (e.g., a gimbal assembly), which may be relatively heavy and prone to mechanical failure, need not be used for steering the at least one antenna reflector, for example. However, relatively large scan angles may be obtained by using the reflector without having to electrically steer the beam over the entire scan angle, which results in less signal loss. Yet, since the phased array antenna is advantageously operable in the direct mode it may also be used as a traditional phased array, which may be desirable when smaller scan angles are required, for example.

[0019] The reflector antenna system may further include a transmitter. Moreover, the controller may connect the transmitter to the second antenna elements when in the reflecting mode, and it may connect the transmitter to the plurality of elements in the second array when in the direct mode. Similarly, the reflector antenna system may also include a receiver, and the controller may connect the receiver to the second antenna elements when in the reflecting mode, and to the plurality of elements in the second array when in the direct mode.

[0020] In addition, a respective phase shifter may be connected between each pair of back-to-back first antenna elements, and the controller may control a phase of the phase shifters. Further, a respective gain element may also be connected between each pair of back-to-back first antenna elements, and the controller may control a gain of the gain elements.

[0021] Each of the antenna elements may be a dipole antenna element including a medial feed portion and a pair of legs extending outwardly therefrom, and adjacent legs of adjacent dipole antenna elements may include respective spaced apart end portions. By way of example, the spaced apart end portions may have predetermined shapes and relative positioning to provide increased capacitive coupling between the adjacent dipole antenna elements. Furthermore, a respective impedance element may be electrically connected between the spaced apart end portions of adjacent legs of adjacent dipole antenna elements. Each respective impedance element may be at least one of an inductor and a capacitor, for example.

[0022] A method aspect of the invention is for using a phased array antenna, such as the one described briefly above. The method may include positioning the phased array antenna in a first antenna beam defined by at least one antenna reflector having an arcuate shape so that the first array faces the at least one antenna reflector and the second array faces away from the at least one antenna reflector. The method may also include selectively switching the phased array antenna between a reflecting mode and a direct mode. More particularly, in the reflecting mode the array may illuminate or feed the reflector antenna surface, and in the direct mode the outer array surface may radiate into free space without illuminating the reflector surface. To switch to the reflecting mode, a plurality of back-to-back pairs of first antenna elements from the first and second arrays are caused to define at least one feed-through zone for the first antenna beam, and a plurality of second antenna

elements in the first array are caused to define at least one first active zone for the first antenna beam. To switch to the direct mode, a plurality of antenna elements in the second array are caused to define at least one second active zone for a second antenna beam.

Brief Description of the Drawings

[0023] FIG. 1 is a perspective view of a reflector antenna system in accordance with the present invention.

[0024] FIG. 2 is schematic block diagram illustrating the phased array antenna of the system of FIG. 1.

[0025] FIG. 3 is a schematic side elevational view of the reflector antenna system of FIG. 1.

[0026] FIG. 4 is a schematic block diagram illustrating phase and gain elements of the phased array antenna of FIG. 2.

[0027] FIGS. 5 and 6 are schematic side elevational views of alternate embodiments of the reflector antenna system of FIG. 1.

[0028] FIG. 7 is an exploded perspective view further illustrating an embodiment of the phased array antenna of FIG. 2.

[0029] FIG. 8 is a plan view of the printed conductive layer of the phased array antenna of FIG. 2.

[0030] FIGS. 9A through 9D are enlarged plan views of various spaced apart end portion configurations of adjacent legs of adjacent dipole antenna elements of the phased array antenna of FIG. 2.

[0031] FIG. 10 is a plan view of the printed conductive layer of another embodiment of the phased array antenna of FIG. 3.

[0032] FIGS. 11 through 13 are flow diagrams illustrating method aspects of the present invention.

Detailed Description of the Preferred Embodiments

[0033] The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout, and prime and multiple prime notation are used to indicate similar elements in alternate embodiments.

[0034] Referring initially to FIGS. 1 through 4, a first embodiment of a reflector antenna system **20** in accordance with the present invention is now described. The system **20** illustratively includes an antenna reflector **21** having an arcuate reflecting surface **22** for defining an antenna beam **23**, as will be appreciated by those skilled in the art. Furthermore, a phased array antenna **24** is positioned in the antenna beam **23**, as shown. More particularly, the phased array antenna **23** is held in place in front of the reflective surface by a plurality of supports **25**, and the reflector **21** may be supported by a mounting base **26**.

[0035] Of course, it will be appreciated that the reflector antenna system **20** in accordance with the present invention may be mounted on numerous land, air,

and spacebourne platforms (e.g., satellites), and the mounting base and relative sizes of the components described herein may vary from one such application to the next. By way of example, the reflector antenna system **20** is particularly well suited for radar and satellite applications, although it may be used for other applications as well, as will be appreciated by those skilled in the art.

[0036] The phased array antenna **24** illustratively includes a substrate **34** and first and second arrays **26, 27** mounted thereon, each including a plurality of antenna elements **400**. More particularly, the arrays **26, 27** preferably have a same number of antenna elements **400** and are selectively connected in back-to-back relation so that respective elements in both arrays can form back-to-back pairs of elements, as will be discussed further below. Of course, not all antenna elements **400** need to be connected in such a back-to-back relationship in all embodiments, as will also be discussed further below. By way of example, the elements **400** may be dipole elements, but patch arrays, etc., may be used as well. Generally speaking, the choice of antenna elements used will depend on the particular application and the bandwidth required, as will be appreciated by those skilled in the art.

[0037] In particular, the phased array antenna **24** also illustratively includes a controller **30** for configuring the antenna elements **400** of the arrays **26, 27**. That is, the controller **30** is connected to a switching network in the substrate **34** (not shown) for selectively connecting respective antenna elements as back-to-back pairs, and/or or to a transmitter **31** or receiver **32**, depending upon the

particular mode of operation of the system **20**. The switching network may be a transistor switching network, for example, or other suitable switching arrangements suitable for use in phased array antenna applications, as will be appreciated by those skilled in the art.

[0038] More particularly, the controller **30** causes a plurality of elements **400** in the second array **27** to be connected to the transmitter **31** or receiver **32** to define an active zone, which illustratively includes the antenna elements within the dashed box **33** (FIG.2). That is, the transmitter **31** provides a feed **29** to the active zone antenna elements **400** for the antenna reflector **21** when the system is transmitting, or it receives the feed from the antenna reflector using the receiver **32** when the system is receiving. FIGS. 1 and 3 illustrate the case when the elements **400** in the active zone are transmitting. However, the opposite case (i.e., reception) would appear the same except that the arrows on the feed **29** and the antenna beam **23** would be reversed, as will be appreciated by those skilled in the art.

[0039] Moreover, the controller **30** also configures a plurality of back-to-back pairs of antenna elements **400** from both arrays **26, 27** to define a feed-through zone for the antenna beam **23**, which in the illustrated example includes all of the antenna elements outside the dashed box **33**. It should be noted that while a single active zone and a single feed-through zone are shown in the present example, in some embodiments more than one active zone and/or feed-through zone may be defined. Moreover, different transmitters and receivers may be connected to different active zones to provide a multi-beam

configuration, such as for transmitting/receiving beams having different polarities, or beams with different bandwidths, as will be appreciated by those skilled in the art.

[0040] When the phased array antenna **24** is configured to include the feed-through zone, it advantageously allows the antenna beam **23** to pass therethrough, as shown in FIGS. 1 and 3. Accordingly, it will be appreciated that the phased array antenna **24** may be placed in front of the antenna reflector **21**, yet without the large amount of blockage that would otherwise occur by similarly using a comparably sized prior art array antenna. The only blockage will occur in the area of the active zone, which may be comparable with or less than that of prior art reflector antennas having a horn or microstrip array in front of the reflector.

[0041] Accordingly, the active zone antenna elements **400** may be used to electrically steer the antenna beam **23**, and thus a mechanical steering assembly (e.g., a gimbal assembly), which may be relatively heavy and prone to mechanical failure, need not be used for steering the antenna reflector **21**. However, relatively large scan angles (e.g., corresponding to greater than about ten times beamwidth (BW)) are obtained by using the antenna reflector **21** without having to electrically steer the beam over the entire scan angle, which results in less signal loss.

[0042] A respective phase shifter **85** may be connected between respective pairs of back-to-back antenna elements **400a, 400b** in the feed-through zone and/or the active zone, and the phase of the phase shifters is controlled

by the controller **30**, as illustrated in FIG. 4. Only a single pair of antenna elements **400a**, **400b** and the respective phase shifter **85** therefor is shown for clarity of illustration. The controller **30** causes the phase shifters **85** to provide the appropriate beamsteering, as required in a given implementation. By including a respective phase shifter **85** between all of the back-to-back pairs **400a**, **400b**, this advantageously allows the controller **30** to re-configure (i.e., move) the active and feed-through zones to different locations, since phase shifting can be performed at all locations as needed.

[0043] In some embodiments, it may also be desirable to similarly connect a respective gain element **87** between respective pairs of back-to-back antenna elements **400a**, **400b** in the feed-through zone and/or the active zone. The controller **30** also controls the gain of the gain elements **87**, as necessary. It will be appreciated by those skilled in the art that the various phase/gain control operations may in some embodiments be spread across multiple controllers arranged in a hierarchy, instead of being performed by the single controller **30**. This approach may be particularly advantageous for larger antenna arrays, for example.

[0044] The phase shifters **85** and gain elements **87** between each pair of back-to-back dipole antenna arrays **400a**, **400b** may be connected in series, as shown. In particular, the antenna elements **400a**, **400b**, phase shifter **85**, and gain element **87** may be connected by transmission elements **88**, which may be coaxial transmission lines, for example. Of course, other

suitable feed structures known to those of skill in the art may also be used.

[0045] Additionally, the phase shifters **85** and gain elements **87** may be positioned between (or within) respective ground planes **300** (FIG. 7) of the first and second arrays **26, 27**. Further details regarding suitable coupling structures for connecting the first and second arrays **26, 27** in a back-to-back relationship to provide electromagnetic (EM) signal feed-through may be found in U.S. Patent No. 6,417,813, which is assigned to the present Assignee and is hereby incorporated herein in its entirety by reference.

[0046] A first method aspect of the invention for using the phased array antenna **24** will now be described with reference to FIG. 11. The method begins (Block **1100**) by positioning the phased array antenna in the antenna beam **23** defined by the antenna reflector **21**, at Block **1101**. Furthermore, a plurality of back-to-back pairs of first antenna elements **400** are configured to define the feed-through zone for the antenna beam **23**, at Block **1102**, while a plurality of second antenna elements are configured to define the active zone for the antenna beam, at Block **1103**, as discussed above, thus concluding the illustrated method (Block **1104**).

[0047] Referring to FIG. 5, an alternate embodiment of the reflector antenna system **20'** illustratively includes a feed device **40'** spaced apart from the antenna reflector **21'**. Here, the phased array antenna **24'** is positioned in the antenna beam **23'** and between the antenna reflector **21'** and the feed device **40'**. As before, a plurality of back-to-back pairs of first antenna elements **400** are

configured to define the feed-through zone for the antenna beam **23'**. However, a plurality of back-to-back pairs of second antenna elements **400** (i.e., the pairs of elements not in the feed-through zone) are configured to provide an active beamsteering zone. That is, the active beamsteering zone antenna elements **400** steer the feed **29'** from the feed device **40'** to the reflector **21'** during transmission, and conversely steer the feed from the reflector to the feed device during reception.

[0048] In this regard, the active beamsteering zone in this embodiment also performs a feed-through function, although the feed **29'** may be redirected based upon the position on the feed device **40'**. An exemplary implementation of a similar phased array antenna lens system for re-directing signals in this fashion is set forth in a co-pending application REDIRECTING FEEDTHROUGH LENS ANTENNA SYSTEM AND RELATED METHODS, attorney docket no. GCSD-1301 (51372), which is assigned to the present Assignee and is hereby incorporated herein in its entirety by reference.

[0049] Accordingly, in the present embodiment, the transmitter and/or receiver (e.g., a transceiver **42'**) is connected to the feed device **41'**. By way of example, the feed device **41'** may be a horn carried by a gimbal **41'**. However, the feed device **40'** could also be another phased array antenna, for example. The illustrated embodiment may be particularly advantageous in that it may allow for a simpler phased array antenna **24'** architecture to be used. For example, to implement this approach the phased array antenna may still include the switching network and

phase shifters **85** discussed above, but may not require the gain elements **87** (e.g., amplifiers).

[0050] A corresponding method aspect of the invention will now be described with reference to FIG 12. The method begins (Block **1200**) with positioning the phased array antenna **24′** between the antenna reflector **21′** and the feed device **41′**, and in the antenna beam **23′** (Block **1201**), as described previously above. Furthermore, back-to-back pairs of first antenna elements **400** are configured to define the feed-through zone for the antenna beam **23′**, at Block **1202**, and back-to-back pairs of second antenna elements are configured to define the active beamsteering zone, at Block **1203**, as also described above, thus concluding the illustrated method (Block **1204**).

[0051] Turning now to FIG. 6, yet another embodiment of the reflector antenna system **20′′** for providing multi-mode operation is now described. More particularly, in the present embodiment, the controller **30** is switchable between a reflecting mode and a direct mode. In the reflecting mode, the controller **30** configures the first and second arrays **26′′**, **27′′** as described above so that the reflector antenna system **20′′** operates exactly as described with reference to FIG. 3. Thus, when the controller **30′′** is in the reflecting mode, the antenna reflector **21′′** defines the antenna beam **23**.

[0052] However, when the controller **30′′** is switched to the direct mode, the controller causes a plurality of antenna elements **400** in the second array **27′′** (which faces away from the antenna reflector **21′′**) to define a second active zone for a second antenna beam **43′′**. That

is, the array **27''** operates in a traditional phased array antenna mode where the antenna beam is directly transmitted or received from the antenna elements thereof. In the illustrated example, the second antenna beam **43''** is shown as a plurality of arrows to indicate that the beam is generated across the entire array **27''**, although not all of the antenna elements thereof need be used for transmitting/receiving the beam in all embodiments, as will be appreciated by those skilled in the art.

[0053] Another advantageous feature of the phased array antenna **24''** is that elements in either array **26''**, **27''** may be shorted to the ground plane **300**, which causes the elements to act as reflectors, as will be appreciated by those skilled in the art. This feature may advantageously be used in any of the above-described configurations to provide still further functionality as desired.

[0054] The direct mode may be desirable when only relatively small scan angles (e.g., corresponding to less than about ten times the BW) are required, for example. However, as noted above, the reflecting mode may be used to provide greater scan angles. Accordingly, this configuration provides a significant amount of versatility, and may in some applications be used to replace multiple antennas.

[0055] A corresponding method aspect of the invention is now described with reference to FIG. 13. The method begins (Block **1300**) with positioning the phased array antenna **24''** in a first antenna beam **23** defined by the antenna reflector **21''** so that the first array **26''** faces

the antenna reflector and the second array **27''** faces away from the antenna reflector, at Block **1301**, as described above. Moreover, if the controller **30** is switched to the reflecting mode, then a plurality of back-to-back pairs of first antenna elements **400a, 400b** from the first and second arrays **26''**, **27''** are caused by the controller to define a feed-through zone for the first antenna beam **23**, at Block **1303**.

[0056] Furthermore, a plurality of second antenna elements **400** in the first array **26''** are caused by the controller **30** to define a first active zone for the first antenna beam, at Block **1304**. However, if the controller **30** is switched to the direct mode, then a plurality of antenna elements **400** in the second array **27''** are caused to define a second active zone for a second antenna beam **43''**, at Block **1305**, as previously described above, thus concluding the illustrated method (Block **1306**).

[0057] It should be noted that various types of reflectors may be used in accordance with the present invention. For example, the arcuate reflecting surface **22** may have a generally parabolic shape, or the antenna reflector **21** may resemble a portion of a cylinder, as will be appreciated by those skilled in the art. Moreover, the arcuate reflector surface **22** may be defined by a plurality of reflector panels, which may individually be flat. Furthermore, in some embodiments more than one reflector may be used. For example, first and second reflectors could be used to define a Casagrain configuration, as will be appreciated by those skilled in the art. Various other configurations that will be

appreciated by those skilled in the art may be used as well.

[0058] Referring additionally to FIG. 7-10, an exemplary wideband antenna array **100**, which may be used for the arrays **26, 27** noted above, will now be described. The wideband antenna array **100** may be formed of a plurality of flexible layers, as shown in FIG. 7. These layers include a dipole layer **200**, or current sheet, which is sandwiched between a ground plane **300** and a cap layer **280**. Additionally, dielectric layers of foam **240** and an outer dielectric layer of foam **260** are provided. Respective adhesive layers **220** secure the dipole layer **200**, ground plane **300**, cap layer **280**, and dielectric layers of foam **240, 260** together to form the flexible and conformal antenna **100**. Of course, other ways of securing the layers may also be used, as will be appreciated by the skilled artisan.

[0059] The dielectric layers **240, 260** may have tapered dielectric constants to improve the scan angle. For example, the dielectric layer **240** between the ground plane **300** and the dipole layer **200** may have a dielectric constant of 3.0, the dielectric layer **240** on the opposite side of the dipole layer **200** may have a dielectric constant of 1.7, and the outer dielectric layer **260** may have a dielectric constant of 1.2. It should be noted that other approaches may also be used to make the antenna **100** operate without the upper dielectric layers **240, 260**. However, generally speaking it is typically desirable to include the dielectric layers **240, 260** above the layer **200**.

[0060] Referring now to FIGS. 8, 9A and 9B, a first embodiment of the dipole layer **200** will now be described. The dipole layer **200** is a printed conductive layer having an array of dipole antenna elements **400** on a flexible substrate **230**. Each dipole antenna element **400** comprises a medial feed portion **420** and a pair of legs **440** extending outwardly therefrom. Respective feed lines are connected to each feed portion **420** from the opposite side of the substrate, as will be described in greater detail below.

[0061] Adjacent legs **440** of adjacent dipole antenna elements **400** have respective spaced apart end portions **460** to provide increased capacitive coupling between the adjacent dipole antenna elements. The adjacent dipole antenna elements **400** have predetermined shapes and relative positioning to provide the increased capacitive coupling. For example, the capacitance between adjacent dipole antenna elements **400** may be between about 0.016 and 0.636 picofarads (pF), and preferably between 0.159 and 0.239 pF.

[0062] As shown in FIG. 9A, the spaced apart end portions **460** in adjacent legs **440** have overlapping or interdigitated portions **470**, and each leg **440** comprises an elongated body portion **490**, an enlarged width end portion **510** connected to an end of the elongated body portion. Each leg **440** further comprises a plurality of fingers **530** (e.g., four) extending outwardly from the enlarged width end portion.

[0063] Alternately, as shown in FIG. 9B, adjacent legs **440′** of adjacent dipole antenna elements **400′** may have respective spaced apart end portions **460′** to provide

increased capacitive coupling between the adjacent dipole antenna elements. In this embodiment, the spaced apart end portions **460′** in adjacent legs **440′** comprise enlarged width end portions **510′** connected to an end of the elongated body portion **490′** to provide the increased capacitance coupling between the adjacent dipole antenna elements. Here, for example, the distance K between the spaced apart end portions **460′** is about 0.003 inches. Of course, other arrangements which increase the capacitive coupling between the adjacent dipole antenna elements are also contemplated by the present invention.

[0064] By way of example, to further increase the capacitive coupling between adjacent dipole antenna elements **400**, a respective discrete or bulk impedance element may be electrically connected across the spaced apart end portions of adjacent legs **440′′** of adjacent dipole antenna elements, as illustrated in FIG. 9C. In the illustrated embodiment, the spaced apart end portions **460′′** have the same width as the elongated body portions connected to an end of the elongated body portions **490′′**.

[0065] The discrete impedance elements **700′′** are preferably soldered in place after the dipole antenna elements **400** have been formed so that they overlay the respective adjacent legs **440′′** of adjacent dipole antenna elements **400**. This advantageously allows the same capacitance to be provided in a smaller area, which helps to lower the operating frequency of the antenna array **100**.

[0066] The illustrated discrete impedance element includes a capacitor **720′′** and an inductor **740′′** connected together in series. However, other

configurations of the capacitor **720''** and inductor **740''** are possible, as will be readily appreciated by those skilled in the art. For example, the capacitor **720''** and an inductor **740''** may be connected together in parallel, or the discrete impedance element **700''** may include the capacitor without the inductor or the inductor without the capacitor. Depending on the intended application, the discrete impedance element **700''** may even include a resistor.

[0067] The discrete impedance element **700''** may also be connected between the adjacent legs **440** with the overlapping or interdigitated portions **470** illustrated in FIG. 9A. In this configuration, the discrete impedance element **700''** advantageously provides a lower cross polarization in the antenna patterns by eliminating asymmetric currents which flow in the interdigitated capacitor portions **470**. Likewise, the discrete impedance element **700''** may also be connected between the adjacent legs **440''** with the enlarged width end portions **510'** illustrated in FIG. 9B.

[0068] Another advantage of the respective discrete impedance elements **700''** is that they may have impedance values so that the bandwidth of the antenna array **100** can be tuned for different applications, as would be readily appreciated by those skilled in the art. In addition, the impedance is not dependent on the impedance properties of the adjacent dielectric layers **240** and adhesives **220**. Since the discrete impedance elements **700''** are not effected by the dielectric layers **240**, this approach advantageously allows the impedance between the

dielectric layers **240** and the impedance of the discrete impedance element **700''** to be decoupled from one another.

[0069] Yet another approach to further increase the capacitive coupling between adjacent dipole antenna elements **400** includes placing a respective printed impedance element **800'''** adjacent the spaced apart end portions of adjacent legs **440'''** of adjacent dipole antenna elements **400**, as illustrated in FIG. 9D. The respective printed impedance elements are separated from the adjacent legs **440'''** by a dielectric layer, and are preferably formed before the dipole antenna layer **200** is formed so that they underlie adjacent legs **440'''** of the adjacent dipole antenna elements **400**.

[0070] Alternately, the respective printed impedance elements **800'''** may be formed after the dipole antenna layer **200** has been formed. For a more detailed explanation of the printed impedance elements and antenna element configurations, reference is directed to U.S. Patent Application Serial Nos. 10/308,424 and 10/634,036, both of which are assigned to the current Assignee of the present invention and are hereby incorporated herein in their entireties by reference.

[0071] The array of dipole antenna elements **400** may be arranged at a density in a range of about 100 to 900 per square foot. The array of dipole antenna elements **400** are sized and relatively positioned so that the antenna array **100** is operable over frequency range of about 2 to 30 GHz, and at a scan angle of about ±60 degrees (low scan loss). Such an array **100** may also have a 10:1 or greater bandwidth, includes conformal surface mounting, while

being relatively lightweight, and easy to manufacture at a low cost.

[0072] For example, FIG. 9A is a greatly enlarged view showing adjacent legs **440** of adjacent dipole antenna elements **400** having respective spaced apart end portions **460** to provide the increased capacitive coupling between the adjacent dipole antenna elements. In the example, the adjacent legs **440** and respective spaced apart end portions **460** may have the following dimensions: the length E of the enlarged width end portion **510** equals 0.061 inches; the width F of the elongated body portions **490** equals 0.034 inches; the combined width G of adjacent enlarged width end portions **510** equals 0.044 inches; the combined length H of the adjacent legs **440** equals 0.276 inches; the width I of each of the plurality of fingers **530** equals 0.005 inches; and the spacing J between adjacent fingers **530** equals 0.003 inches.

[0073] In the example (referring to FIG. 8), the dipole layer **200** may have the following dimensions: a width A of twelve inches and a height B of eighteen inches. In this example, the number C of dipole antenna elements **400** along the width A equals 43, and the number D of dipole antenna elements along the length B equals 65, resulting in an array of 2795 dipole antenna elements. The wideband antenna array **100** may have a desired frequency range, e.g., 2 GHz to 18 GHz, and the spacing between the end portions **460** of adjacent legs **440** may be less than about one-half a wavelength of a highest desired frequency.

[0074] Referring to FIG. 10, another embodiment of the dipole layer **200’** may include first and second sets of

dipole antenna elements **400** which are orthogonal to each other to provide dual polarization, as will be appreciated by the skilled artisan. The antenna array **100** may be made by forming the array of dipole antenna elements **400** on the flexible substrate **230**. This preferably includes printing and/or etching a conductive layer of dipole antenna elements **400** on the substrate **230**. As shown in FIG. 10, first and second sets of dipole antenna elements **400** may be formed orthogonal to each other to provide dual polarization.

[0075] Again, each dipole antenna element **400** includes the medial feed portion **420** and the pair of legs **440** extending outwardly therefrom. Forming the array of dipole antenna elements **400** includes shaping and positioning respective spaced apart end portions **460** of adjacent legs **440** of adjacent dipole antenna elements to provide increased capacitive coupling between the adjacent dipole antenna elements. Shaping and positioning the respective spaced apart end portions **460** may include forming interdigitated portions **470** (FIG. 9A) or enlarged width end portions **510'** (FIG. 9B), etc. A ground plane **300** is preferably formed adjacent the array of dipole antenna elements **400**, and one or more dielectric layers **240, 260** are layered on both sides of the dipole layer **200** with adhesive layers **220** therebetween.

[0076] Forming the array of dipole antenna elements **400** may further include forming each leg **440** with an elongated body portion **490**, an enlarged width end portion **510** connected to an end of the elongated body portion, and a plurality of fingers **530** extending outwardly from the enlarged width end portion. Again, the wideband

antenna array **100** has a desired frequency range, and the spacing between the end portions **460** of adjacent legs **440** is less than about one-half a wavelength of a highest desired frequency. The ground plane **300** is spaced from the array of dipole antenna elements **400** less than about one-half a wavelength of the highest desired frequency.

[0077] As discussed above, the array of dipole antenna elements **400** are preferably sized and relatively positioned so that the wideband phased array antenna **100** is operable over a frequency range of about 2 GHz to 30 GHz, and operable over a scan angle of about ±60 degrees.

[0078] It should also be noted that there can be different geometrical arrangements of dipole elements **40** that can provide for the transmission or rejection of polarized waves. The phased array antenna **24** may be configured with an arrangement of dipole elements **400** oriented in one direction, providing a single linear polarization (the terms "vertical" or "horizontal" are often used but a single linear polarization may have any orientation relative to a given reference angle) or may include crossed dipoles which would provide for a more general antenna solution. Crossed dipoles, nominally oriented at ninety degrees to one another (see FIG. 10) provide two basis vectors from which any sense linear or elliptical polarization may be formed with appropriate phasing of the elements, as will be appreciated by those skilled in the art. Of course, other geometrical or element arrangements for polarization control may also be used, as will also be appreciated by those skilled in the art.

[0079] Additional features of the invention may be found in the co-pending applications entitled REFLECTOR ANTENNA SYSTEM INCLUDING A PHASED ARRAY ANTENNA HAVING A FEED-THROUGH ZONE AND RELATED METHODS, attorney docket number GCSD-1297 (51368), and REFLECTOR ANTENNA SYSTEM INCLUDING A PHASED ARRAY ANTENNA OPERABLE IN MULTIPLE MODES AND RELATED METHODS, attorney docket number GCSD-1299 (51370), the entire disclosures of which are hereby incorporated herein by reference.

[0080] Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.